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GAMMA RAYS FROM POINT GALACTIC SOURCES

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ABSTRACT

Propagation of nuclei through a background photon field is analyzed in order to obtain γ-ray spectra from photonuclear and photopion reactions. The results are used for estimation of the effectiveness of the VHE γ-ray production by point galactic sources. It demonstrates the potential importance of the processes of γ-ray production involving background photons.

Subject headings: gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

In recent papers (Karakula & Tkaczyk 1991, 1993), the mass composition of high-energy cosmic rays (HE CR) and their energy spectrum have been analyzed following the idea suggested by Hillas (1979). In that model, mass composition and spectrum of HE CR are formed by photonuclear and photopion reactions with soft photons in the CR source region. The considered model well describes the observed CR energy spectrum in a wide energy range.

This study is a further consideration of the CR model by Karakula & Tkaczyk (1991, 1993). Propagation of relativistic protons and nuclei through a soft photon field is analyzed in order to investigate processes of generation of VHE γ-rays. The photonuclear and photopion production processes occurring in the vicinity of a CR source are included. The results obtained are used for estimations of the effectiveness of the VHE γ-ray generation by point galactic sources. The preliminary results have been reported during the 22d International Cosmic Ray Conference (Karakula et al. 1991).

The units $h/2\pi = c = 1$ are used in the paper.

2. THE GAMMA-RAY ENERGY SPECTRA

2.1. *Exact Solutions*

To obtain the spectrum of VHE gamma rays, we solve the following transfer equation (which does not include a γe-cascade), which at high energies can be treated one-dimensionally:

$$\frac{\partial \Gamma_{N,p}(E_\gamma, x)}{\partial x} = -s(E_\gamma)\Gamma_{N,p}(E_\gamma, x) + Q_{N,p}(E_\gamma, x)\,, \tag{1}$$

where $\Gamma_N(E_\gamma, x)$ and $\Gamma_p(E_\gamma, x)$ are the numbers of VHE gamma-quanta with energy E_γ from photonuclear and photopion processes, respectively, at the propagation distance x and in units of s^{-1} MeV^{-1}; $s(E_\gamma)$ is the inverse mean free path of VHE gamma-quanta against the pair production $\gamma\gamma \rightarrow e^+e^-$ in homogeneous and isotropic background field; $Q_{N,p}(E_\gamma, x)$ are the VHE γ-ray source functions, which represent the emission (from photonuclear and photopion reactions, respectively) in the outward direction at the propagation distance x per unit of radius per 1 s per energy interval and are in units of s^{-1} MeV^{-1} cm^{-1} (Karakula et al. 1991, 1993).

Equation (1) describes the generation and absorption of VHE γ-rays during the particle propagation in a background photon field. The propagation distance x imagines the distance from the source. For effective γ-ray production such a background field should be thick enough but that leads to strong absorption of VHE γ-rays due to pair production $\gamma\gamma \rightarrow e^+e^-$. In this case the integral $\int E_\gamma \Gamma(E_\gamma, x) dE_\gamma$ above the threshold of e^-e^+-pair creation gives us the total radiated energy that is a parameter for the saturated cascade description (Berezinsky et al. 1990). If the source is surrounded by a thin photon field, accelerated particles should be retained near the source for effective γ-ray production (e.g., by its magnetic field). In this case, the propagation distance x imagines the path which those accelerated particles passed by the moment, while the VHE γ-rays can escape freely [it could be obtained by taking $s(E_\gamma) = 0$ in the equation]. Both cases are discussed in detail in §§ 2.2 and 3; here we give the general solution of equation (1).

Nuclear VHE γ-rays are created through deexcitation of relativistic nuclear fragments arising from photonuclear reactions (Balashov et al. 1987, 1990). The number of excited nuclei per unit of the path length is $a_A(E)N_A(E, x)dE$, where A is the mass number, $a_A(E)$ is the inverse mean free path of the nucleus against the reaction, and $N_A(E, x)$ is the flux of the nuclei A with an

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energy E per nucleon at the propagation distance x. The γ-ray source function is

$$Q_N(E_\gamma, x) = \frac{\bar{n}M}{2\bar{E}_\gamma} \int_{E_0}^{\infty} \frac{dE}{E} \sum_{A \le 56} a_A(E) N_A(E, x) , \tag{2}$$

where $\bar{n}$ is the mean multiplicity of secondary γ-quanta per the reaction; $\bar{E}_\gamma$ is the mean energy of secondary γ-quanta; and M is the nucleon rest mass, $E_0 = ME_\gamma/2\bar{E}_\gamma$. In general, values of $\bar{n}$ and $\bar{E}_\gamma$ are unknown. For iron nuclei, they were calculated by Moskalenko & Fotina (1989): $\bar{n} \approx 2$ and $\bar{E}_\gamma \approx 2.5$ MeV; these values are used for further calculations.

The total flux of γ-rays from the photonuclear reactions is

$$\Gamma_N(E_\gamma, x) = \frac{\bar{n}M}{2\bar{E}_\gamma} \int_{E_0}^{\infty} \frac{dE}{E} \sum_{A \le 56} a_A(E) \sum_{56 \ge B \ge A} b_{AB}(E) \frac{\exp[-a_B(E)x] - \exp[-s(E_\gamma)x]}{s(E_\gamma) - a_B(E)} \tag{3}$$

where the coefficients $b_{AB}(E)$ can be found as follows:

$$b_{AA}(E) = N_A(E, 0), \qquad \text{for} \qquad A = 56$$

$$b_{AA}(E) = N_A(E, 0) - \sum_{56 \ge C > A} b_{AC}(E), \qquad \text{for} \qquad A < 56$$

$$b_{AB}(E) = \frac{a_{A+1}(E) b_{A+1B}(E)}{a_A(E) - a_B(E)}, \qquad \text{for} \qquad 56 \ge B > A .$$

The photopion source function $Q_p(E_\gamma, x)$ can be obtained from equation (2) by replacing $\bar{E}_\gamma = KM/2$, $\bar{n} = 2$, $a_A(E) \rightarrow g(E)$, $N_A(E, x) \rightarrow P(E, x)$. Here the inelasticity coefficient $K = 0.3$ is assumed to be independent of the primary energy of a proton, $g(E)$ is the inverse mean free path length of proton against photopion production, and $P(E, x)$ is the flux of protons with an energy E at the propagation distance x. The γ-ray flux from the process is

$$\Gamma_p(E_\gamma, x) = \frac{2}{K} \int_{E_\gamma/K}^{\infty} \frac{dE}{E} g(E) \sum_{l \ge 0} \tilde{P}_l(E, E_\gamma, x) , \tag{4}$$

where

$$\tilde{P}_l(E, E_\gamma, x) = \begin{cases} P(E, x = 0) \dfrac{\exp[-g(E)x] - \exp[-s(E_\gamma)x]}{s(E_\gamma) - g(E)}, & \text{for} \quad l = 0 \\ \dfrac{P\{[E/(1-K)^l], x = 0\}}{(1-K)^l} \displaystyle\prod_{j=1}^{l} g\left(\frac{E}{(1-K)^j}\right) \sum_{n=0}^{l} \frac{1}{s(E_\gamma) - g[E/(1-K)^n]} & \\ \times \dfrac{\exp\{-g[E/(1-K)^n]x\} - \exp[-s(E_\gamma)x]}{\prod_{m=0, m \ne n}^{l} \{g[E/(1-K)^m] - g[E/(1-K^n]\}}, & \text{for} \quad l > 0 \end{cases} \tag{5}$$

and $P(E, 0)$ is the proton flux at $x = 0$.

2.2. *The Approximate Formulae*

2.2.1. *Small Propagation Distances*

In those energy regions where x is smaller or comparable with the mean free path of primary protons, the source function Q_p can be obtained analytically. If the spectrum of background photons is a power-law type ($f_0\epsilon^{-\delta}$), then the source function is (Karakula et al. 1991, 1993)

$$Q'_p(E_\gamma, x) = 2P(0) \frac{\sigma_{\gamma p} f_0 \omega M}{K\delta(\alpha + 1 - \delta)} \left(\frac{\omega M}{2}\right)^{-\delta} (E_\gamma/K)^{\delta-\alpha-1} , \tag{6}$$

where $P(0)$ is the normalization constant $P(E, 0) = P(0)E^{-\alpha}$, $\sigma_{\gamma p} \approx 200$ μbarn, $K = 0.3$ is the inelasticity coefficient, ω is the $\Delta(1232)$ resonance excitation energy. The π^0-production cross section is approximated with δ-function: $\sigma(E') = \sigma_{\gamma p} E' \delta(E' - \omega)$, where E' is the energy of soft photons in the proton rest system. The spectrum of VHE γ-rays (without absorption) is $\Gamma_p(E_\gamma, x) = \eta x Q_p(E_\gamma, x)$, where $\eta = 1.15, 0.91, 0.77$ for $\delta = 1.3, 1.5, 1.7$, correspondingly. The values $\eta = \eta(\delta)$ have been obtained from the comparison of results of formulae (4) and (6).

In the case of a blackbody background field, the source function has been obtained by Stecker (1973). In the energy region $E_\gamma \leq \omega MK/(2\bar{\epsilon})$, that formula reduced to

$$Q_p''(E_\gamma, x) = 2P(0)\frac{\sigma_{\gamma p} n_{ph}}{K(\alpha+1)}[\omega MK/(2\bar{\epsilon})]^{-\alpha}, \quad (7)$$

where $n_{ph} = 0.244(kT)^3$ and $\bar{\epsilon} \approx 2.7kT$ are the number density and the mean energy of blackbody photons, respectively, and kT is their temperature.

2.2.2. *Asymptotic Formulae* ($x \rightarrow \infty$)

If the protons lose all their energy via photopion production the asymptotic spectrum of γ-rays from the reaction is

$$\Gamma_p(E_\gamma) = P(0)E_\gamma^{-\alpha}K^{\alpha-2}/(\alpha-1). \quad (8)$$

The photonuclear cross section is much higher than photopion one so accelerated nuclei disintegrate quickly. When the nuclei are disintegrated at all, the spectrum of γ-rays is

$$\Gamma_N(E_\gamma) = \sum_A N_A(0)\frac{AM\bar{n}}{2\alpha\bar{E}_\gamma}(E_\gamma M/2\bar{E}_\gamma)^{-\alpha}, \qquad \text{for} \qquad E_\gamma \geq 2E_{\rm th}\bar{E}_\gamma/M, \quad (9)$$

where $N_A(0)$ is the normalization constant $N_A(E, 0) = N_A(0)E^{-\alpha}$ and $E_{\rm th}$ is the nucleus threshold energy (per nucleon) of the reaction in the laboratory system.

3. RESULTS AND DISCUSSION

Interactions of VHE cosmic-ray particles with interstellar matter had been analyzed in numerous papers in order to obtain the energy spectra of diffuse γ-rays and neutrinos. Taking into account the galactic interstellar matter distribution and CR energy spectrum, it is possible to estimate the diffuse flux of VHE γ-rays. However, the best experimental limits achieved with an air shower array do not approach the diffuse flux calculated under the assumption that the CR spectrum is the same everywhere in the disk of the Galaxy as observed at Earth (Berezinsky et al. 1993). An additional contribution to the diffuse flux of VHE γ-rays could arise from the photopion and photonuclear reactions occurring in the vicinity of HE CR sources as was shown by Karakula et al. (1991).

A reasonable model of a CR source has been described by Karakula & Tkaczyk (1991, 1993). In that model, (1) point galactic sources produce nuclei ($A = 1$–56) with a power-law energy spectrum $\alpha = 2.6$, (2) their composition is the same as in the Tien Shan experiment at 1.5×10^{15} eV (see Table 1), and (3) the mass composition and the spectrum of HE CR are formed by photonuclear and photopion reactions with soft photons in the source region. The energy spectra of nuclei and their mass composition at an arbitrary propagation distance have been obtained by solving appropriate diffusion equations (Karakula & Tkaczyk 1993). The parameters of the background photon field have been obtained from the best fit of the calculated CR energy spectrum to the experimental one: for the power-law background photon spectrum, $f_0 = 10^{12}$ MeV$^{0.3}$ cm^{-3}, $\delta = 1.3$, $\epsilon' = 20$ eV (ϵ' is cut off at higher energies); for the blackbody spectrum, $kT = 1.8$ eV; the propagation distance of the nuclei as calculated is $x_0 = 10^{14.4}$ cm. These fitted spectra of background photons are used in further calculations.

The generation of VHE γ-rays in a CR source is considered from the viewpoint of the above-mentioned model. The VHE γ-rays are produced by γp- and γA-reactions with background photons in the CR source region. If the CR source is surrounded by a thin photon field, then the magnetic field around the source is needed to retain the particles near the source (to convert their energy into the gammas). Strength of the magnetic field can be obtained from that the Larmor radius of the particles must be less than mean free path of γ-rays: $H(\mathrm{G}) \geq E(\mathrm{eV})s(\mathrm{cm}^{-1})/(300\,Z)$, where E is the total particle energy and Z is the charge number. For a proton of $E \sim 10^{17}$ eV and $1/s \sim 10^{10}$ cm, the field of $H \sim 3000$ G is needed that is typical for a neutron star environment. In this case the spectrum at higher energies ($>10^8$ MeV) is determined by the photopion reactions. The photonuclear reactions give the main

TABLE 1

MASS COMPOSITION OF CR AT THE ENERGY 1.5×10^{15} eV PER NUCLEUS (Nikolsky 1984)

Group of Nuclei	Mass Composition
p ($A = 1$)	39% ± 4%
α ($A = 2$–4)	13 ± 7
M ($A = 10$–16)	17 ± 5
H ($A = 17$–40)	17 ± 5
VH ($A > 40$)	18 ± 5

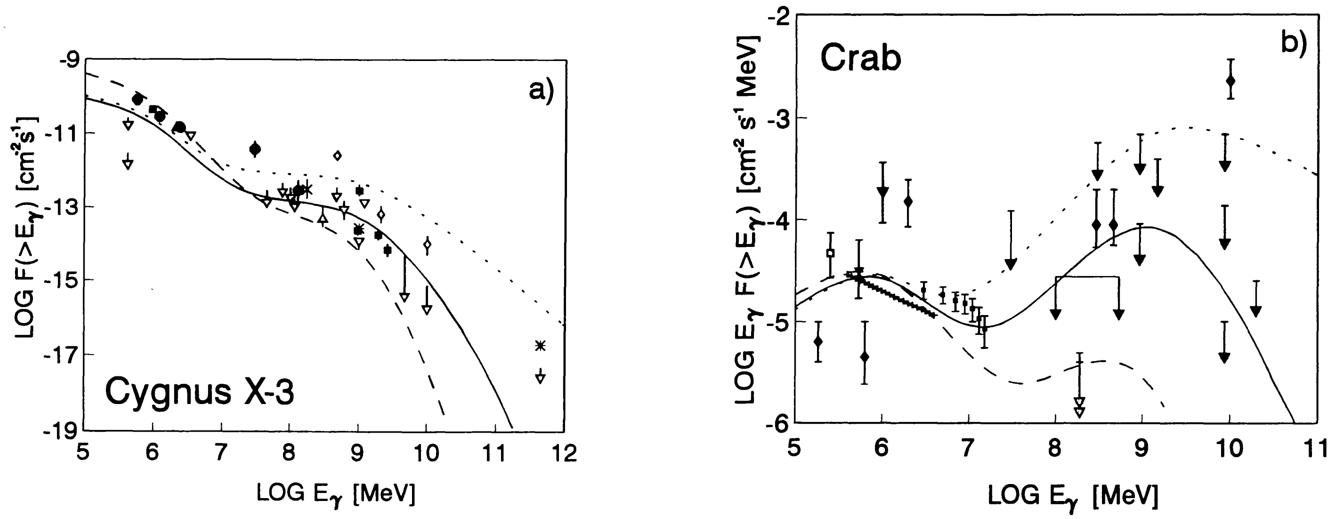

FIG. 1.—The integral γ-ray spectra from the directions of Cygnus X-3 and the Crab Nebula. The spectra are shown for certain values of the thickness of the background photon field: *dotted line*, $D = 0$ (without absorption); *solid line*, $D = 1 \times 10^{10}$ cm; *dashed line*, $D = 3 \times 10^{10}$ cm. The experimental data in Fig. 1*a* were compiled by Berezinsky et al. (1990). The experimental data in Fig .1*b* were taken from Vacanti et al. (1991) (*plus signs*), Baillon et al. (1993) (*shaded squares*); upper limits were given by Borione et al. (1993) (*open triangles*), and the other was compiled by Berezinsky et al. (1990). The calculated spectra are normalized to the experimental points at $\sim 10^6$ MeV.

contribution up to 10^8 MeV. If the CR source is surrounded by an extended field of soft photons, the VHE γ-rays are absorbed by the $\gamma\gamma \rightarrow e^+e^-$ process, so the γe-cascade should develop and the γ-ray spectrum can be observed at an energy region < 100 GeV only.

The integral γ-ray spectra from the directions of Cygnus X-3 and the Crab Nebula are shown in Figure 1 for the case of the power-law background photon spectrum. The attenuation of the primary VHE γ-rays was considered to be following $\Gamma(\geq E_\gamma, x) = \int dE_\gamma \Gamma(E_\gamma, x) \exp[-Ds(E_\gamma)]$, where D is an effective thickness of the background photon field.

New data and upper limits for Cyg X-3 reported during the 23d International Cosmic Ray Conference are in agreement with the old points (Fig. 1*a*) compiled by Berezinsky et al. (1990). Those are well described by calculated curves for $D = 1 \times 10^{10}$ cm and 3×10^{10} cm.

Figure 1*b* shows the spectra from the direction of the Crab Nebula. The data compiled by Berezinsky et al. (1990) and new points by Vacanti et al. (1991) and Baillon et al. (1993) at TeV energies are well described by the calculated spectra with $D = 1 \times 10^{10}$ cm, while new upper limits at higher energy ($\approx 2 \times 10^8$ MeV) by Borione et al. (1993) do not contradict the calculations for $D = 3 \times 10^{10}$ cm. It could be connected with evolution of the source and around a photon field or with the higher accuracy of the modern measurements. The spectral index we used ($\delta = 1.3$) for calculations is approximately the same as is observed $\delta = 1.25$ for the Crab pulsar in eV energy range (Cheng, Ho, & Ruderman 1986).

Using formulae (8) and (9), it is easy to estimate the hadronic luminosity of a source in VHE range. The γ-ray luminosity of Cyg X-3 in the 2–2000 TeV energy range is $W_\gamma \approx 1 \times 10^{37} \times (R/10\ \mathrm{kpc})^2(\Omega/4\pi)$ ergs s^{-1} (Berezinsky 1987). If the main contribution to this radiation is coming from photonuclear reactions, then the corresponding particle luminosity, as estimated from formula (9), is $W_1 \approx W_\gamma \alpha M/(2\bar{n}\bar{E}_\gamma \bar{A}) \approx 7.2 \times 10^{39} \times (R/10\ \mathrm{kpc})^2(\Omega/4\pi)[0.1/\Delta/P]$ ergs s^{-1}. Here $\bar{A} = \sum_A AN_A(0)/\sum_A N_A(0) \approx 3.4$ is the mean mass composition of primary nuclei (without protons) at the same energy per nucleon as can be obtained from Table 1, R is the distance from the source, Ω is a solid angle of the γ-ray emission, Δ is the duration of the γ-ray pulse, and $P = 4.8$ hr. If such γ-ray luminosity is coming from photopion reactions, the required proton luminosity (as estimated from formula [8]) is $W_2 \approx W_\gamma(\alpha - 1) \approx 1.6 \times 10^{38}(R/10\ \mathrm{kpc})^2(\Omega/4\pi)[0.1/\Delta/P]$. Similar calculations for the Crab pulsar give $W_1 \approx 3.6 \times 10^{36}$ ergs s^{-1} and $W_2 \approx 8 \times 10^{34}$ ergs s^{-1} from formulae (9) and (8), respectively, assuming the observed γ-ray luminosity $\approx 5 \times 10^{34}$ ergs s^{-1} above 1 TeV. These are reasonable upper and lower limits on the VHE hadronic emission from the sources.

The results presented demonstrate the potential importance of processes with background photons for VHE γ-ray production in point sources as well as diffusive sources. As was shown by Berezinsky et al. (1993), the best experimental limits achieved with an air shower array do not approach the diffuse flux calculated under the assumption that such flux is originated from interactions of VHE cosmic-ray particles with interstellar matter. An additional contribution to the diffuse flux of the VHE γ-rays could arise from the photopion and photonuclear reactions occurring in the vicinity of unresolved sources as was discussed above. For such estimations, it is necessary to take into account the spatial distribution of such sources in the Galaxy and their power distribution; that is a subject for investigation in future papers.

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